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Cogent Food & Agriculture (2017), 3: 1386438



Received: 21 August 2017
 Accepted: 27 September 2017
 First Published: 03 October 2017

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Reviewing editor:
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 Seville, Spain

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Assessing opportunities for selective winery vintage with a market-driven composite index

Jaume Arnó^{1*} and José A. Martínez-Casasnovas²

Abstract: An opportunity index (OI_{sv}) is proposed for selective vine harvest management to ensure vineyard sustainability making use of precision farming technologies. Vigour maps derived from remote sensors are the basis of the method. In terms of validation, the index was applied in 36 vineyard fields of different varieties in Raimat (Lleida, northeast Spain). The OI_{sv} is based on three components: (i) the spatial variability in vine vigour (to ensure variability in the quality of grapes), (ii) the spatial structure or pattern of vigour (to facilitate harvesting operations), and (iii) the availability of a minimum productive quality area within the plot (to ensure that benefits derived from the differentiation of the final product will compensate for the expenses of differential management). The results suggest that only few plots were suitable for selective vintage, although an acceptable agreement was obtained when comparing the plots harvested selectively by the winery and those classified as favourable by the OI_{sv} . The method is reliable and also allows varying the parameter specifications according to the logistics of each winery and/or actual market conditions. However, currently, the OI_{sv} can only be applied at plot level and future versions should address application at the whole vineyard scale.

Subjects: Agricultural Engineering; Crop Science; Horticulture

Keywords: selective harvesting; opportunity index; vine vigour; NDVI; decision support systems; geostatistics

ABOUT THE AUTHORS

Jaume Arnó and José A. Martínez-Casasnovas are members of the Research Group in AgroICT & Precision Agriculture (GRAP) at the University of Lleida (Catalonia, Spain). Their current research activities are collaborative, and focus on the use of sensors in agriculture (crop and soil sensors), spatial data analysis, new efficient methods for field sampling, and systems to aid decision-making in the framework of precision agriculture. Concerning the latter, taking the decision on site-specific crop management using an opportunity index is an option to continue studying. The reasons are the immediacy of its application and the practical results that it reports to farmers and managers.

PUBLIC INTEREST STATEMENT

Precision Viticulture (PV) is an increasingly accepted concept in the viticultural sector. Putting into practice PV, farmers and winemakers can take advantage of the use of information technologies to assist in decision-making. Specifically, remote satellite imagery can report very interesting information on vineyards with high spatial resolution, converting crop reflectance signals into suitable vegetation indices such as Normalized Difference Vegetation Index (NDVI). As NDVI is an indirect measure of vine vigour, NDVI maps make it possible to have detailed information on vine spatial variability within the plots. When this variation is associated with another significant variation in grape quality parameters, separate harvesting of the highest quality grapes can add value to the final product. In this paper, a method to evaluate selective vintage opportunity through NDVI map analysis is proposed. In order to successfully complete the procedure, certain knowledge in geostatistics and appropriate software are required.

1. Introduction

Previous research in the field of precision viticulture (PV) has shown that vineyard yield and vigour vary within a field with some correlation, and the pattern of variation of both these variables also presents a significant spatial structure (Bramley & Hamilton, 2004, 2007). It is also known that both yield and vigour have relationships with some grape maturity and grape quality parameters (Arnó, Rosell, Blanco, Ramos, & Martínez-Casasnovas, 2012; Bramley, 2005; Bramley, Ouzman, & Boss, 2011; Martínez-Casasnovas, Agelet-Fernández, Arnó, & Ramos, 2012). Then, given the price differentiation between grapes of different quality, selective harvesting based on prior classification of vigour maps may produce homogenous blocks of varying quality within the plots and yield higher benefits (Bramley, Proffitt, Hinze, Pearse, & Hamilton, 2005), even when large fermentation volumes are used for winemaking (Bramley, Ouzman, & Thornton, 2011). However, it is important to understand whether there are sufficient and structured spatial variations of yield and/or vigour (and consequently, in certain parameters related to grape quality) to undertake differential management for a given vineyard field. Furthermore, winemakers and technical managers first need to identify areas with the best quality grapes (those that will command a higher market price) and then evaluate whether this area is large enough to justify investing in the needed equipment and devices for selective harvesting. Arnó, Martínez-Casasnovas, Ribes-Dasi, and Rosell (2009) reported on several opportunity indices (OIs) developed in the context of PV to assess the opportunity for differential management within a field, as well as to establish a ranking of vineyards within a farm according to their index values. However, these indices are usually based only on the yield spatial variability and often do not take into account other aspects related to the economy of the production process.

The concept of OIs is well known. However, all the OIs proposed to date have strengths and weaknesses. Pringle, McBratney, Whelan, and Taylor (2003) presented an OI based on two components: field variability (spatial variability) and spatial distribution of this variability (spatial structure). The same dichotomous scheme was used by De Oliveira, Whelan, McBratney, and Taylor (2007) in an index that focuses mainly on arable crops. For viticulture specifically, the spatial footprint of agricultural machinery plays a key role in the OIs proposed by Paoli, Tisseyre, Strauss, and McBratney (2010), and Tisseyre and McBratney (2008). Using a similar approach, Roudier, Tisseyre, Poilvé, and Roger (2011) proposed another index adapted to zone management in viticulture and other crops. In all cases, the performance of these indices was shown to be satisfactory. However, the opportunity is evaluated only from a technical point of view and does not consider other aspects related to the economy of operations and/or farm size. A simplified index to assess the opportunity for selective wine grape harvesting depending on operational economy was initially proposed by Monsó, Arnó, and Martínez-Casasnovas (2013), and the current paper presents an enhanced version. There are two noteworthy characteristics. First, the proposed version is novel in that the index is only based on vigour maps derived from high-resolution remote sensing data. Vigour maps are preferred to yield maps, because the latter require special harvesting machines (available in a few wineries only). Also, data acquisition by yield monitors is not exempt from errors or equipment malfunction, and thus, continuous coverage of data cannot be assured. Another advantage is that the remote sensing data are acquired during veraison in the same campaign, unlike yield maps that need to be collected across previous campaigns. Second, the method adds a parameter that considers the productive plan and logistics of the winery. Specifically, the index specifies the minimum amount of quality grapes (or minimum productive quality area in hectares) to be harvested separately to ensure that the process is economical. Thus, the index is now extended to three components: spatial variability, spatial structure, and the surface area occupied by quality grapes.

Selective vintage offers opportunities mainly to large companies with flexible winery infrastructure (Bramley et al., 2011). Thus, our study is focused toward such stakeholders. In addition, successful implementation is likely to require the use of software and technologies that already enjoy an increasingly widespread application in the wine sector, mainly by the industry, such as remote sensing and geographic information systems (GIS and open source versions). In short, the OI is designed to be applied by a big winery in Raimat (Lleida, northeast Spain), to classify vineyard plots using GIS software and according to the opportunities for selective harvesting for two different

Figure 1. Selective vintage in Raimat (Lleida, Spain).

Note: The harvester puts the grapes in one trailer or the other depending on the selective harvesting zone it is passing through.



qualities of grape (Figure 1). The following sections show how the OI is defined for the case under study but without loss of generality, since it is open to further adjustments to suit other wineries and their particular management logistics.

2. Opportunity index for selective vintage

The calculation for the Opportunity index for selective vintage (OI_{sv}) consists of two phases. First, the normalized difference vegetation index (NDVI) and the corresponding raster maps (vigour maps) are obtained at the plot level. In our case, the NDVI was obtained from a multispectral satellite image (Quickbird-2 with 2.7 m resolution) acquired at the end of July 2006 (± 2 weeks from veraison). Note that there may be reasonable doubts about the optimal timing of image acquisition. Following Lamb, Weedon, and Bramley (2004), this study assumes that veraison is the optimum time to predict grape phenolics and colour. However, other stages in the growth process can be considered, as the strength of correlation between the NDVI and anthocyanins/total phenolics may be even more consistent after veraison (Hall, Lamb, Holzapfel, & Louis, 2011; Urretavizcaya et al., 2014).

Second, the NDVI values are analysed to obtain the OI_{sv} based on three components. To determine the most suitable fields for selective vintage, the first component to consider is the spatial variability of NDVI values. Assuming that vines with lower vigour (low NDVI values) produce higher quality grapes (Bramley et al., 2011), only fields with a large magnitude of variation in the vigour of vines would present distinct grape quality. The second parameter concerns the need for the spatial variation to be highly structured in order to optimize the operation and working time of the grape harvester. In other words, the spatial structure of the NDVI should be strong enough to be technically manageable (Tisseyre & McBratney, 2008). Once these two requirements are achieved, a minimum area containing high quality grapes is needed to ensure the profitability (economy) of the process. According to this approach, the OI_{sv} can be formulated in terms of these three components, so that vineyard fields have to reach a particular threshold for each component in order to be considered suitable for selective harvesting. Following Pringle et al. (2003), the OI_{sv} in this study is expressed as shown in Equation (1):

$$OI_{SV} = f \left[\left(\frac{\text{Parameter that measures the spatial variation of NDVI}}{\text{Threshold}_v} \right) \times \left(\frac{\text{Parameter that measures the spatial structure of NDVI}}{\text{Threshold}_s} \right) \times \left(\frac{\text{Parameter that measures the area with lower NDVI}}{\text{Threshold}_A} \right) \right] \quad (1)$$

As the formulation shows, it is necessary to analyse the NDVI values at plot level by combining different statistical procedures. Besides a previous descriptive analysis, obtaining the variograms in the direction of the rows of vines is essential; grape harvesters work along the rows, and the structure of spatial variation needs to be known in this direction. Some authors claim to include this functionality in zoning methods (Roudier, Tisseyre, Poilvé, & Roger, 2008), and experience also suggests that within-field NDVI variability usually indicates anisotropy in vineyard fields. So, to display the dissimilarity of NDVI as a function of the separation distance between two sampling points, a geostatistical analysis was performed for each field using directional variograms along the vine rows. This is a basic feature that differentiates the OI_{SV} from the other indexes that have been proposed in the scientific literature. Obviously, calculating the directional variogram adds some complexity to the method, but it is a key aspect given the operation of field grape harvesters. On the other hand, and given its widespread use in soil science and agriculture, the spherical model was assumed as the ad hoc model and was adjusted to fit the spatial correlations in NDVI values. This approach may be questionable, because it ignores other possible variogram models. However, the spherical model is preferred since it allows the subsequent use of some adjusted variogram parameters that are required to analyse the spatial structure of NDVI values. The software ArcGIS 10.1 (ESRI) is the recommended option to perform this variographic analysis and calculate the other components of the OI_{SV} . Entering the detail, the methods used to obtain each component of Equation (1) are explained in the following sections.

2.1. Spatial variability (S_v)

The spatial variation of the NDVI in a plot can be measured using the Coefficient of Variation (CV). However, Pringle et al. (2003) suggested using an adjusted CV using the so-called structural variance in NDVI values. Following this recommendation, we proposed a spatially structured coefficient of variation (CV_s), which is calculated using the structural (autocorrelated) variance (C_1) of the corresponding directional-adjusted variogram (namely variance that could be explained by the spatial dependence of the NDVI data) (see Figure 2 for a visual explanation). The square root of C_1 is divided by the mean NDVI of the plot (μ) and multiplied by 100 to obtain the CV_s :

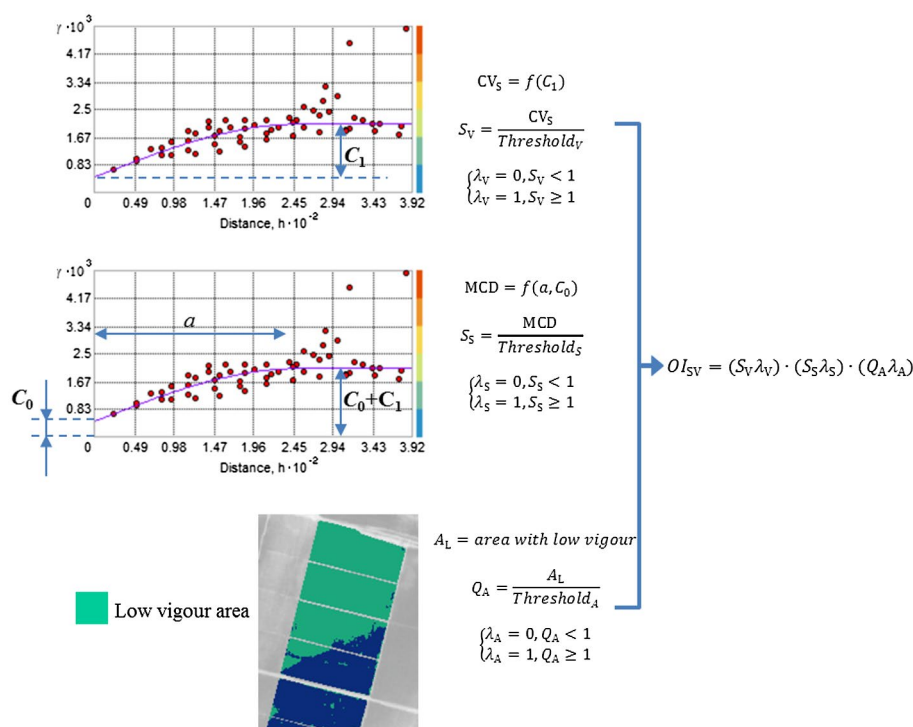
$$CV_s = \frac{\sqrt{C_1}}{\mu} \times 100 \quad S_v = \frac{CV_s}{\text{Threshold}_v} \quad (2)$$

The threshold is set as the median value of the coefficients of all tested vineyard fields, in this case, 14.5%. Note that a minimum NDVI variation is necessary to justify differential management. The selected value moves away from the threshold (25.6%) established by Pringle et al. (2003) in a similar study. Nevertheless, in the latter, the median was calculated for different crops using yield maps. The threshold (14.5%) should not be taken as fixed. The winery can change this value from one campaign to another. Moreover, any winery that uses the index can adjust the threshold value to their needs and according to previous experience.

2.2. Spatial structure (S_s)

The spatial structure of the NDVI along vine rows can be assessed using the Mean Correlation Distance (MCD) calculated from the directional variogram. This parameter was first defined by Han, Hummel, Goering, and Cahn (1994) to select areas with certain nearly uniform properties that can be used as the upper limit of the cell size for applying variable-rate inputs in site-specific crop management strategies. In our case, the MCD may be taken as the maximum distance that the machine

Figure 2. Opportunity index calculation process. (i) The structural variance (C_1) is obtained from the directional variogram, and it is then used to calculate the parameter measuring the spatial variability of the NDVI. The result is divided by the threshold value, 14.5%. (ii) The range (a) and nugget variance (C_0) from the directional variogram are used to evaluate the spatial structure along the rows (Mean Correlation Distance or MCD), with the threshold set at 50 m. (iii) The low vigour area (A_L) obtained by cluster analysis is divided by the threshold value of 3 ha. The OI_{SV} is calculated as the product of the three components.



can move along a row for harvesting grapes of the same quality. Considering the parameters of a bounded spherical variogram model (a variogram in the direction of the rows), the MCD can be calculated as seen in Equation (3),

$$MCD = \frac{3}{8} \times \left(\frac{C_1}{C_0 + C_1} \right) \times a \quad S_S = \frac{MCD}{\text{Threshold}_S} \quad (3)$$

where C_0 is the “nugget” variance of the adjusted variogram, $C_0 + C_1$ is the sill (variance that can be attributed to the plot studied), and a is the range (distance after which the NDVIs do not exhibit spatial dependence or autocorrelation). Given that the MCD integrates the range and nugget effect in the same coefficient, it provides a very interesting insight into the extension (distance) of spatial dependence at plot level. It is easier to selectively harvest a field with large patterns of variation (large variogram range).

The next step is to set the corresponding threshold. The aim is to establish the minimum row distance for the same grape quality so as to optimize the working time of the harvester, taking into account the manner of selective harvesting practised by the winery. The winery company in Raimat uses grape harvesters with side discharge belts in combination with two tractor-trailer units moving in parallel to the harvester (Figure 1). This operating procedure is adopted for selective vintage that separates only two grape qualities corresponding to two vigour (NDVI) classes. The threshold is set at a distance of 50 m. This value was agreed upon with the winery staff. In European winegrape production systems (particularly in Spain and Portugal), grape harvesters normally operate at speeds ranging between 0.8 and 1.4 m s^{-1} , achieving operating times from 1.5 to 2 h ha^{-1} . For selective vintage, this operating time normally increases, since it is necessary to stop the grape harvester and then change the position of the tractors every time the harvester moves from an area of one grape quality to another of a different grape quality. In order to limit operating costs, the most valuable fields are those that can be harvested with fewer changes. Assuming that the operating time of a selective harvest should not exceed a certain percentage (α) of the time of a conventional harvest

($\alpha = 0.1$, since 10% was suggested by managers for the case study winery), the maximum number of stops (changes in position) due to changes in grape quality can be determined using Equation (4),

$$N \leq \frac{\alpha \times T_{\text{Ocv}} \times 3600}{t_{\text{CSV}}} \quad (4)$$

where α is the percentage assumed (0.1, in the present case), T_{Ocv} is the operating time (h ha^{-1}) for conventional vintage, and t_{CSV} (s) is the time required (~ 10 s) to change the position of the tractor to begin collecting grapes of a different quality. Equation (4) was applied to the study area, where vine rows are planted at 3.2 m. The resulting maximum number of stops (changes of position) per hectare lies between 54 and 72, with a threshold distance ranging from 43.4 to 57.8 m. A number of factors govern the optimal threshold, with each factor possibly resulting in a different minimum distance. However, the value of the adopted threshold (~ 50 m) is reasonable and consistent with the average distance from the obtained interval; it is long enough to reduce positional changes and not affect the working time. Thus, dividing the MCD by 50 in Figure 2 allow us to evaluate the spatial structure of NDVI values within the plot. Unlike the previous component (spatial variability), this threshold value is totally conditioned by the specific harvesting system used in the winery under study. In case of using grape harvesters that can perform a selective vintage without needing to unload the grape in a continuous way, managers of the winery could also fix an optimum threshold value linked to the optimization of the operating time and cost. This case has not been contemplated in this paper.

2.3. Quality area (Q_A)

To quantify the area with high quality grapes, an unsupervised classification-based clustering algorithm (Isodata, ArcGIS 10.1) is applied to the NDVI maps, limiting us to only two classes of vigour (low and high) in line with the winery's strategy. The area with low vigour (A_L) can be estimated after applying the classification algorithm (Figure 2). The quality area component (Q_A) is finally obtained as:

$$Q_A = \frac{A_L}{\text{Threshold}_A} \quad (5)$$

The idea of using NDVI values to differentiate grape quality is well known, assuming that less vigorous vines produce higher quality grapes. However, there are some drawbacks. As discussed by Bramley et al. (2011), the often-assumed negative correlation between grape yield (vine vigour) and quality is not always true, and thus, special care should be taken when making management decisions based on a single layer of spatial data such as the NDVI. Moreover, remote images should be complemented with sampling in order to properly delineate areas with oenological significance at harvest times (Urretavizcaya et al., 2014). Despite these difficulties, there have been many successful experiences in the use of vegetation indices in viticulture, and wineries tend to appreciate the spatial classification of remote sensing images, as it is simple, fast, and affordable. In fact, the winery presented in this study has had previous experience in separating two classes of grape quality and delimiting two well-defined areas producing markedly different wines based on the exclusive use of the plant cell density (PCD) vegetation index. Finally, the OI_{sv} is based on a flexible design concept so that the user can not only modify the applied vegetation index and classification algorithm but can also combine one or more data layers to better define the spatial variation in quality.

The reasoning for the selection of the threshold is simple. The market plays a decisive factor, and the additional costs resulting from selective harvesting and product streaming should be balanced by higher selling prices. From this economic point of view, a minimum area of high quality grapes is required considering the volumes of the fermentation tanks in the winery. Bramley et al. (2011) provided very interesting results in this respect. They demonstrated that selective harvesting is economically viable in Australia even when the tanks are not used to full capacity. Adopting the same approach for scenarios of increasing demand for quality wines in Europe, the mapping of low NDVI

areas (higher quality grapes) should exceed 3 ha, since this is the minimum area required to fill the tanks in Raimat (40 t ferment) to two-thirds of their capacity for winemaking. The fixed threshold, the quality component of the OI_{SV} , is finally computed as shown in Figure 2. Wineries with other capacities are free to adopt another area as threshold value.

To clearly distinguish suitable fields (those presenting the opportunity), each component of the OI_{SV} is finally affected by a lambda function as shown in Equation (6). This function takes the value “1” when the parameter exceeds the corresponding threshold and “0” otherwise, the idea being that the fields with the best characteristics for selective harvesting obtain higher OI_{SV} values. In contrast, fields that fail in terms of any of the analysed components will have an OI_{SV} of zero, thus indicating that no opportunity exists for differential management.

$$OI_{SV} = (S_V \times \lambda_V) \times (S_S \times \lambda_S) \times (Q_A \times \lambda_A) \quad (6)$$

$$\begin{cases} \lambda_V = 0, S_V < 1 \\ \lambda_V = 1, S_V \geq 1 \end{cases} \quad \begin{cases} \lambda_S = 0, S_S < 1 \\ \lambda_S = 1, S_S \geq 1 \end{cases} \quad \begin{cases} \lambda_A = 0, Q_A < 1 \\ \lambda_A = 1, Q_A \geq 1 \end{cases}$$

3. Case study

The research was carried out in 36 commercial vineyard fields located in Raimat (lat. 41°39'50.5"N; long. 00°29'53"E) (Figure 3). This area is included in the Costers del Segre Designation of Origin. It is a semi-arid area with a continental Mediterranean climate, receiving a total annual precipitation from 300 to 400 mm. The fields measure 2 to 25 ha, and the main varieties of grape are Merlot, Chardonnay, Pinot Noir, Tempranillo, Cabernet Sauvignon, Malbec, and Syrah. The vines are irrigated by either drip irrigation or sprinklers. The former is usually used for partial root drying schedules. The soils are classified as Fluventic Haploxerepts, Calcic Haploxerepts, and Typic Haploxerepts (Soil Survey Staff, 2006). The last may present a paralithic barrier within the first 50 cm, which could represent a limitation for vine development. Descriptive details and the mean values of the NDVI and coefficients of variation for each field are given in Table 1.

Figure 3. Location map of the study area.

Note: The boundaries of the 36 experimental fields are depicted in black.

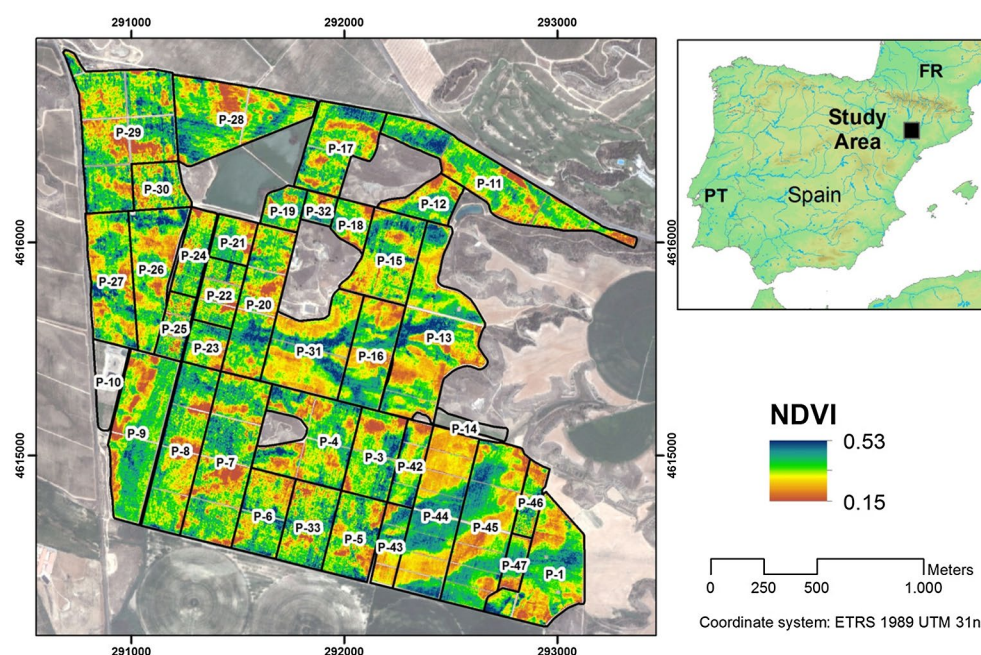


Table 1. Plots and descriptive analysis of NDVI values

Plot number	Cultivar	Area (ha)	Training system	Irrigation system	NDVI mean	NDVI CV (%)
P01	Merlot	15.26	VSP ^a	Drip	0.332	12.7
P03	<i>Chardonnay</i>	8.99	VSP	Sprinkler	0.427	14.5
P04	Pinot Noir	14.83	Ballerina	Sprinkler	0.330	17.6
P05	Merlot	8.61	VSP	Sprinkler	0.343	13.4
P06	Tempranillo	8.36	VSP	Sprinkler	0.379	13.7
P07	<i>Chardonnay</i>	19.74	VSP	Sprinkler	0.367	14.7
P08	Merlot	14.98	VSP	Sprinkler	0.346	16.5
P09	Merlot	16.92	VSP	Drip	0.340	12.9
P11	<i>Chardonnay</i>	17.77	NP ^b	Sprinkler	0.442	12.0
P12	Cabernet Sauvignon	5.00	T Trellis	Sprinkler	0.372	15.1
P13	<i>Chardonnay</i>	23.58	VSP	PRD ^c	0.317	21.1
P15	Pinot Noir	11.11	Ballerina	Drip	0.341	12.9
P16	<i>Sauvignon Blanc</i>	10.25	VSP	PRD	0.329	19.1
P17	Cabernet Sauvignon	11.69	T Trellis	Sprinkler	0.339	16.8
P18	Cabernet Sauvignon	3.38	T Trellis	Sprinkler	0.387	14.7
P19	Merlot	3.42	NP	Sprinkler	0.369	16.0
P20	Tempranillo	13.56	Smart-Dyson	Sprinkler	0.397	16.4
P21	Cabernet Sauvignon	3.93	T Trellis	Sprinkler	0.365	16.7
P22	Merlot	5.71	T Trellis	Sprinkler	0.347	11.8
P23	Cabernet Sauvignon	3.85	Smart-Dyson	Sprinkler	0.351	12.0
P24	<i>Albariño</i>	5.21	VSP	Sprinkler	0.381	8.9
P25	Cabernet Sauvignon	3.96	T Trellis	Sprinkler	0.363	12.1
P26	Pinot Noir	12.13	VSP	Drip	0.334	16.8
P27	<i>Chardonnay</i>	12.58	VSP	Drip	0.325	14.5
P28	<i>Chardonnay</i>	17.47	VSP	Sprinkler	0.345	16.8
P29	Cabernet Sauvignon	25.12	VSP	Sprinkler	0.360	16.1
P30	Pinot Noir	5.28	VSP	Sprinkler	0.406	12.6
P31	Tempranillo	15.00	VSP	Drip	0.297	19.5
P32	Cabernet Sauvignon	2.05	NP	Sprinkler	0.444	12.2
P33	<i>Chardonnay</i>	8.50	Ballerina	Sprinkler	0.411	8.8
P42	Petit Verdot	4.97	VSP	PRD	0.282	16.3
P43	Malbec	4.54	VSP	PRD	0.309	18.4
P44	Syrah	17.74	VSP	PRD	0.338	24.0
P45	<i>Albariño</i>	19.37	VSP	PRD	0.361	20.2
P46	<i>Godello</i>	3.41	VSP	PRD	0.298	15.8
P47	<i>Verdejo</i>	2.57	VSP	PRD	0.410	13.2

Note: The data for the white grapes appear in italics.

^aVertical shoot positioned trellis.

^bNo pruning.

^cPartial rootzone drying.

4. Results and discussion

Table 2 shows the values of the OI_{sv} for the 36 vineyard fields using data from 2006 (first campaign with selective vintage in Raimat). As a first approach, very few vineyard fields showed opportunity for selective harvesting, and only 6 out of the 36 fields were classified as suitable (red grape varieties in fields P08, P42, and P44, and white grape varieties in fields P03, P28, and P45), with their OI_{sv} values lying between 3 and 11 (fields with non-zero value of the index in Table 2).

The OI_{sv} may be regarded as being highly restrictive in terms of its simultaneous requirement for the three parameters to exceed the following threshold values: 14.5% for CV_s , 50 m for MCD, and 3 ha for surface area with high quality grapes (A_1). On the other hand, some discrepancies appeared when fields selected by the OI_{sv} were compared with those actually harvested on a selective basis in 2006. For reasons and specific logistics to that year, the case study winery only conducted selective harvesting in fields with red grapes, in plots P01, P08, P17, P29, and P44. Therefore, the predictions of the OI_{sv} actually matched the reality for two plots only of those where selective vintage was done. This suggested the need for a more detailed discussion of the functioning of the index and the possibility of refining the procedure.

Some fields, like P09 and P20 (Table 2), showed no opportunity, because they narrowly failed to meet the threshold value for one of the parameters of the OI_{sv} . In other cases (e.g. P29), a similar situation occurred for two of the thresholds. To avoid disregarding plots that could be favourable for selective harvesting, the possibility of reducing the respective thresholds and recalculating the OI_{sv} for such fields was considered. Probably, this post correction may seem lacking in robustness. However, we believe that the grower should be able to review the initial results of the OI_{sv} and, based on the experience of previous campaigns, finally decide which plots are eligible for selective harvesting. In this way, it was arbitrarily decided to reduce the relevant threshold value by 20% when the fields failed to exceed the threshold for only one of the parameters and by 10% for each parameter when the corresponding values feel short for two of the thresholds. This procedure added seven new fields to those previously selected as being appropriate for selective harvesting. With the abovementioned modifications, fields P01, P04, and P09 managed to exceed the reduced threshold of 11.6% in the CV_s . Similarly, fields P20 and P31 and field P43 exceeded the reduced thresholds of 40 m for the MCD and 2.4 ha for the clustered area, respectively. For fields with two failures, only P29 exceeded the reduced thresholds of spatial and structural variability of 13.1% and 45 m, respectively. In short, applying these final adjustments increased the number of fields presenting opportunities for selective harvesting to 13, that is, a little over 35% of Raimat's fields. Figure 4 shows the final map after applying the OI_{sv} . The fields presenting opportunities for selective harvesting are highlighted in green. In contrast, one can distinguish fields showing no opportunity (in red) from fields that can be selectively harvested if the threshold values of the OI_{sv} are modified appropriately (in yellow).

To validate the OI_{sv} , a concordance analysis (Table 3) was performed only for the red variety of grapes (24 of the 36 fields), since there was no selective vintage for white varieties in 2006. An overall accuracy of 71% and a kappa index of 0.36 (indicating acceptable agreement) were obtained when comparing the selectively harvested fields in 2006 and the fields with opportunities detected by the OI_{sv} in this study. Specifically, in 17 fields (4 and 13 with and without opportunities, respectively), the OI_{sv} coincided with the approach used by the case study winery. Moreover, selective harvesting was actually conducted in five fields, of which four were also selected by the OI_{sv} (Table 3). The agreement between the actual and calculated numbers could have been higher, but the company did not selectively harvest all the proposed fields due to the product strategies decided by the winemakers. Thus, the OI_{sv} ranged between 2 and 11 (Table 3), enabling the classification of fields into three categories according to the opportunities they presented for selective vintage: low (2–4), medium (5–7), and high (8–11) (Figure 5).

Table 2. Opportunity index (OI_{sv}) for selective vintage

	Spatial variability				Spatial structure				Quality area				$S_V \cdot S_S \cdot Q_A$	Opportunity index (OI_{SV})
	CV_s	$CV_s/14.5$		λ_v	MCD	MCD/50		λ_s	A_L	$A_L/3$		λ_A		
		S_v	S_s			S_s	Q_A			A_A				
Field														
P01	12.05	0.83	0	73	1.46	1	8.48	2.83	1	3.4	0			
P03	14.83	1.02	1	122	2.44	1	4.73	1.58	1	3.9	4			
P04	11.73	0.81	0	80	1.60	1	8.47	2.82	1	3.6	0			
P05	11.90	0.82	0	24	0.48	0	4.69	1.56	1	0.6	0			
P06	12.11	0.83	0	33	0.66	0	5.23	1.74	1	1.0	0			
P07	13.44	0.93	0	34	0.68	0	8.63	2.88	1	1.8	0			
P08	15.94	1.10	1	85	1.70	1	8.25	2.75	1	5.2	5			
P09	12.30	0.85	0	76	1.52	1	5.12	1.71	1	2.2	0			
P11	9.85	0.68	0	75	1.50	1	9.47	3.16	1	3.2	0			
P12	15.37	1.06	1	39	0.78	0	2.31	0.77	0	0.6	0			
P13	20.41	1.41	1	33	0.66	0	14.15	4.72	1	4.3	0			
P15	8.49	0.58	0	35	0.70	0	6.82	2.27	1	0.9	0			
P16	17.89	1.23	1	35	0.70	0	5.57	1.86	1	1.6	0			
P17	11.59	0.80	0	11	0.22	0	6.06	2.02	1	0.4	0			
P18	16.25	1.12	1	44	0.88	0	1.34	0.45	0	0.4	0			
P19	16.16	1.11	1	16	0.32	0	1.28	0.43	0	0.1	0			
P20	15.21	1.05	1	48	0.96	0	7.87	2.62	1	2.6	0			
P21	17.88	1.23	1	74	1.48	1	1.50	0.50	0	0.9	0			
P22	9.94	0.68	0	14	0.28	0	3.11	1.04	1	0.2	0			
P23	11.52	0.79	0	44	0.88	0	1.82	0.61	0	0.4	0			
P24	8.09	0.56	0	62	1.24	1	2.53	0.84	0	0.6	0			
P25	9.13	0.63	0	17	0.34	0	1.79	0.60	0	0.1	0			
P26	16.18	1.11	1	30	0.60	0	7.77	2.59	1	1.8	0			
P27	14.20	0.98	0	29	0.58	0	7.18	2.39	1	1.4	0			
P28	15.49	1.07	1	63	1.26	1	8.73	2.91	1	3.9	4			
P29	14.02	0.97	0	45	0.90	0	11.90	3.97	1	3.4	0			
P30	10.53	0.73	0	18	0.36	0	2.77	0.92	0	0.2	0			
P31	21.03	1.45	1	46	0.92	0	9.50	3.17	1	4.2	0			
P32	13.75	0.95	0	35	0.70	0	0.89	0.30	0	0.2	0			
P33	4.91	0.34	0	43	0.86	0	4.36	1.45	1	0.4	0			
P42	17.19	1.18	1	108	2.16	1	3.28	1.09	1	2.8	3			
P43	20.62	1.42	1	89	1.78	1	2.50	0.83	0	2.1	0			
P44	26.13	1.80	1	92	1.84	1	9.52	3.17	1	10.5	11			
P45	21.38	1.47	1	85	1.70	1	8.81	2.94	1	7.3	7			
P46	15.04	1.04	1	47	0.94	0	1.57	0.52	0	0.5	0			
P47	15.68	1.08	1	51	1.02	1	0.84	0.28	0	0.3	0			

Note: Fields with white grapes are depicted in italics.

Figure 4. Selective harvesting opportunities in 36 vineyard fields in Raimat (Lleida, Spain). (i) Fields in green indicate that the opportunity is present. (ii) Fields in yellow may be harvested selectively after adjusting the OI_{sv} (iii) Fields in red do not present opportunities.

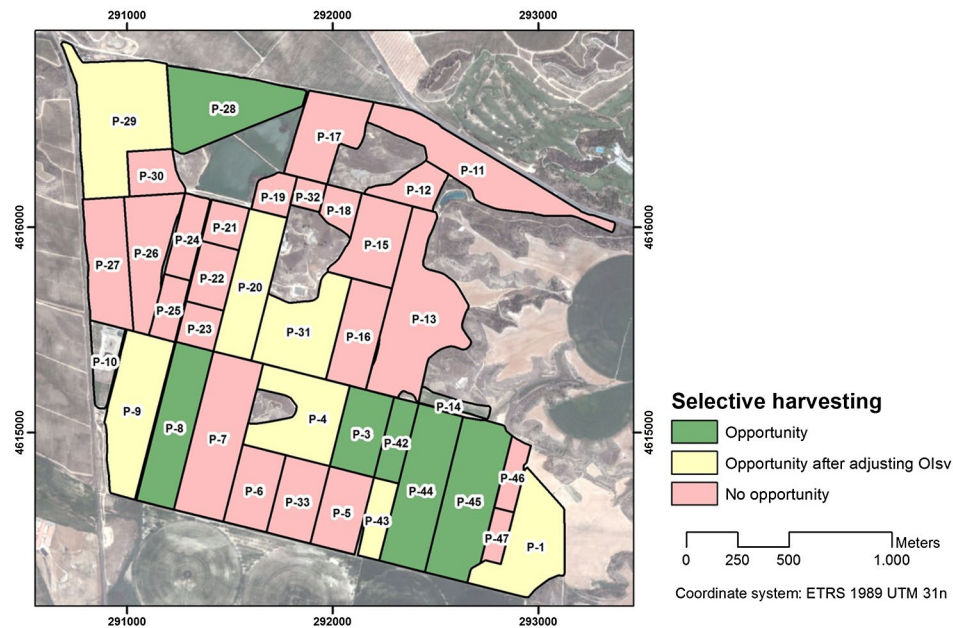
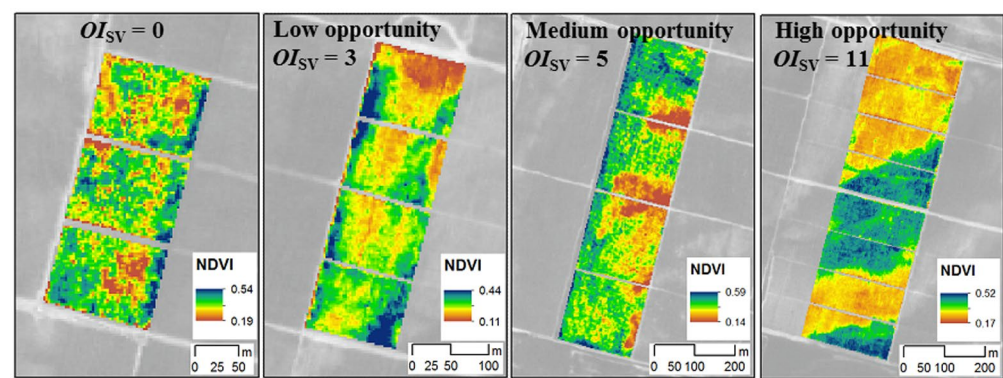


Table 3. Fields with selective vintage opportunity under the proposed index

Field	Spatial variability		Spatial structure		Quality area		Opportunity index (OI_{sv})	Selective vintage in Raimat
	CV_s (%)	S_v	MCD (m)	S_s	A_L (ha)	Q_A		
P01	12.05	0.83	73	1.46	8.48	2.83	3	Yes
P03 ^a	14.83	1.02	122	2.44	4.73	1.58	4	–
P04	11.73	0.81	80	1.60	8.47	2.82	4	No
P08	15.94	1.10	85	1.70	8.25	2.75	5	Yes
P09	12.30	0.85	76	1.52	5.12	1.71	2	No
P20	15.21	1.05	48	0.96	7.87	2.62	3	No
P28 ^a	15.49	1.07	63	1.26	8.73	2.91	4	–
P29	14.02	0.97	45	0.90	11.90	3.97	3	Yes
P31	21.03	1.45	46	0.92	9.50	3.17	4	No
P42	17.19	1.18	108	2.16	3.28	1.09	3	No
P43	20.62	1.42	89	1.78	2.50	0.83	2	No
P44	26.13	1.80	92	1.84	9.52	3.17	11	Yes
P45 ^a	21.38	1.47	85	1.70	8.81	2.94	7	–

^aDenotes fields with white grape varieties.

Figure 5. Selected vigour (NDVI) maps and the opportunity for selective harvesting.



4.1. Issues left open and lessons learned

The OI_{sv} has shown good preliminary results. However, there are some unresolved issues such as whether the OI_{sv} can be used in small plots of small- and medium-sized grape growers who usually supply the fruit to large wineries. The OI_{sv} is designed to be applied discretely; that is, it considers each vineyard block individually. As a result, it is not possible to apply the index to smaller areas growing quality fruit unless many such small-sized plots are combined to exceed the required threshold for grape quantities. In fact, Bramley et al. (2011) referred to this limitation, which is a real possibility in many wineries; depending on the employed winemaking strategies and consumer preferences, wineries may harvest grapes separately even for small areas within a field with the condition that the set of plots (of the own wine cellar or from different vine growers supplying it) offer a minimum quantity of quality grapes. This is a key aspect to be improved in future versions of the opportunity index. Other minor issue is related to the threshold that allows deciding on the spatial structure within the plot. The requirement of a minimum distance of 50 m is reasonable given the particular way of performing the mechanized vintage in the winery under study. Moreover, plots are usually planted by arranging the rows in such a way that the length normally exceeds this distance to optimize operating times and costs. Therefore, plots with particular shapes that require the orientation and planting of rows of small length are not common in a modern and competitive viticulture.

Faced with these potential drawbacks, the proposed opportunity index can be useful as a first approximation given the numerical and graphical information it provides. Figure 4 shows the plots classified by opportunity after applying the OI_{sv} . Winery managers can then identify those fields suitable for selective harvesting but containing small-sized areas of quality grapes (in our case, the fields presenting low opportunity for selective harvesting are depicted in yellow) and can decide to harvest these areas separately to complement grape yields of plots with opportunity (depicted in green in Figure 4), or other homogeneous fields with similar quality of fruit within their property (depicted in red in Figure 4). Thus, by using the OI_{sv} , it is possible to add value to the acquired imagery, which is particularly apt given the increasing use of remote sensing technologies by wineries possessing the needed infrastructure. In practice, the OI_{sv} must be viewed only as a support tool for decision-making; harvesting decisions should not be based solely on the OI_{sv} . We agree with Bramley et al. (2011) in that any decision resulting from the use of remote high-spatial resolution images must be supported with appropriate ground-truthing and sampling.

There is little doubt that selective harvesting can provide economic advantages for a more sustainable and competitive viticulture. Hence, an expert system that includes an OI allowing the efficient manipulation and analysis of remote sensing data is much needed to make it easier for the wine sector to decide on selective vintage.

5. Conclusion

The OI_{sv} is an index that assesses the opportunity for selective harvesting at plot level. Compared to some other indices, the OI_{sv} is relatively simple to calculate since GIS software can be used, and it has the added advantage of using remotely sensed data, an increasingly known and widespread application in the wine-growing sector. The OI_{sv} is designed to be used mainly by wineries. Since winemakers need to plan production according to grape varieties and quality, advanced information about fields that can be harvested evenly and non-homogeneous fields having appropriate characteristics for selective harvesting is of great importance. The OI_{sv} is aimed at identifying the latter, namely fields that can provide the required amounts of quality grapes, and by clearly defining zones of different grape qualities, it also optimizes the operation and working time of grape harvesters. Finally, the proposed OI_{sv} is flexible to use in that some of the parameters adopted in this study can be modified to better suit the requirements of other wineries.

Acknowledgements

This study was possible thanks to the collaboration between the University of Lleida and Codorniu Winery in Raimat (Lleida, Spain).

Funding

The authors received no direct funding for this research.

Competing Interests

The authors declare no competing interest.

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Citation information

Cite this article as: Assessing opportunities for selective winery vintage with a market-driven composite index, Jaume Arnó & José A. Martínez-Casasnovas, *Cogent Food & Agriculture* (2017), 3: 1386438.

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